

The usefulness of marginal CO₂-e abatement cost curves in Austria

Petra Wächter^{a,b,*}



^a Institute of Technology Assessment of the Austrian Academy of Sciences, Strohgassee 45/5, 1030 Vienna, Austria

^b Institute of the Environment and Regional Development, Vienna University of Economics and Business Administration, NordbergstraÙe 15, 1090 Vienna, Austria

HIGHLIGHTS

- Energy efficiency measures on a national level for Austria.
- First Marginal CO₂-e abatement cost curve for Austria.
- Reflections about the applicability of MACCs.
- Measures with negative CO₂-e abatement costs identified that fulfill the Kyoto Protocol.

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ABSTRACT

Energy efficiency measures are manifold in all economic sectors. These measures can be pictured by a marginal abatement cost curve (MACC) which is a common way to show CO₂-e abatement potential and its related costs in various fields. In this paper, we calculated the marginal CO₂-e abatement cost curve for Austria for the first time to fulfill the need for country specific cost curves. One of the strengths of such curves lies in their ability to highlight that energy efficiency measures can even have negative abatement costs. The weaknesses consist of neglecting a change in energy prices, the rate of diffusion, and compatibility with existing technologies. By using a static bottom-up approach we constructed the MACC for four economic sectors (household, service, transport, energy) and found a national mitigation potential of 45.4 million tons CO₂-e. The results further show that even with the measures with negative abatement costs it is possible to make the necessary CO₂-e mitigation to fulfill the Kyoto Protocol. The conclusions emphasize that the curve makes a contribution to overcome one of the barriers of implementation by providing enhanced information on energy efficiency measures and its costs.

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1. Introduction

Climate change and its impacts is one of the most urgent problems in the current social and political debate. Undoubtedly, human activity can be seen as responsible for climate change and therefore it is up to human beings to tackle them. The Kyoto Protocol obliges industrialized countries for the first time to cut CO₂-e emissions by 5.2% on average below the 1990 level by 2012. Austria commits itself to reduce its emissions by 13.2% below the 1990 level which means a rate of permitted emissions of 68.8 million tons (Mt) of CO₂ equivalents (CO₂-e). But implementing compliance of this obligation was too ambitious: In 2009, greenhouse-gas (GHG) emissions exceeded the envisaged rate

with 80.1 Mt CO₂-e resulting in a gap of 11.3 Mt CO₂-e (Federal Environment Agency, 2011).

There are four economic sectors that were seen as responsible for about 85.3% of all GHG emissions (transport, industry, energy production, heating) in 2009 (Federal Environment Agency, 2011). There has been an immense increase of emissions in the transport sector which have risen by 54.4% in the period 1990–2009 (emissions in CO₂-e 1990: 14 Mt; emissions 2009: 21.7 Mt), and the corresponding share in the overall emissions increased from 17.9% to 27.8% (Federal Environment Agency, 2011). According to the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management (2008) reducing the emissions of the transport sector is the biggest challenge to be overcome if Austria is to achieve the goals of the Kyoto Protocol. In the same period the industry sector also recorded an increase in CO₂-e emissions of 5.9%, the biggest polluters being iron and steel production and the mineral processing industry. In this sector, 16.6 of 22.5 Mt are already covered by emissions trading, which is also the reason why the sector was not analyzed in detail. These

* Correspondence address: Institute of Technology Assessment of the Austrian Academy of Sciences, Strohgassee 45/5, 1030 Vienna, Austria. Tel.: +43 1 51581 6592; fax: +43 1 7109883.

E-mail address: petra.waechter@oeaw.ac.at

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two sectors also constitute the largest departure from the Kyoto goal. In the energy-producing sector emissions increased by 17.4% to 16.2 Mt CO₂-e in the period 1990–2005 (Federal Environment Agency, 2008), but after peaking they decreased to 12.8 Mt in 2009, which is even 1 Mt less than in 1990 (Federal Environment Agency, 2011). This can be explained by an increase in the use of renewable energy sources, which have further potential for the production of electricity. The fourth biggest polluter is heating, although emissions decreased by 21.5% in the period 1990–2009, due to building insulation and changes to low-carbon heating systems. Nonetheless, the biggest challenges here remain efficiency improvements in all buildings and heating systems. Unfortunately, the sectors household and service are not accounted for separately in Austria but instead only the category heating is reported including both household and service sector. Emissions from electricity are accounted for in the energy sector as emissions from primary production.

The aim of this paper is to present CO₂-e mitigation options by constructing a marginal abatement cost curve (MACC) for Austria and to critically reflect on the applicability of such curves. By further developing this approach of marginal CO₂-e abatement cost curves, this study analyses various high-impact scenarios to reduce emissions for the household, service, transport and energy supply sectors in Austria. The measures are then ranked according to the costs/ton CO₂-e ratio. The study provides a quantitative basis for (policy) decision makers as a starting point as to which abatement measures can be pursued and conducted in terms of their overall potential, and how much they would cost. The results show that even the measures with negative abatement cost have the potential to reduce CO₂-e exactly to the amount that is needed to fulfill Austria's requirements of the Kyoto Protocol. The paper concludes by emphasizing on how to overcome one of the barriers of implementation of energy efficiency measures by providing further information on the possibilities of reducing energy demand and its costs.

The paper proceeds as follows: Following the introduction, Section 2 shortly describes the barriers of implementation of energy efficiency measures and analyses the results of other studies which used marginal abatement cost curves. Section 3 presents the used method to construct the marginal abatement cost curve for Austria and its further development and explains the data currently used. The discussion in Section 4 shows some advantages of and critical views on MACCs. Section 5 describes the results in general and in more detail for the specific sectors. The paper ends with the conclusions and outlook in Section 6.

2. Marginal abatement cost curves

2.1. Barriers to the implementation of increased energy efficiency and market failures

Although much progress has been made in the past few decades, both on an individual as well as on an overall system level, most economic sectors still show huge unused potential in energy efficiency. Following the energy efficiency improvements already achieved, the question can be raised as to why the regarding actors and institutions have not already made use of this immense potential and as to what the multiple and persistent barriers to increased energy efficiency are (Granade et al., 2009).

The so called energy efficiency gap refers to the difference between observed levels of energy efficiency and some notion of optimal use (Gillingham et al., 2009). Barriers of implementation are present in various economic fields such as orthodox economics, agency theory, economics of information, transaction cost economics and behavioral economics (Sorrell et al., 2004).

Although these different economic approaches have diverging explanations, they widely agree on the main barriers to energy efficiency: risk, imperfect information, hidden cost, access to capital, split incentives and bounded rationality (Sorrell et al., 2004). In practice, each area has its own mix of barriers, with awareness and information, access to capital, and product or service availability the three most commonly observed (Granade et al., 2009). It is exactly that combination of factors which makes it even more difficult and complex and requires more than one single solution to overcome the detected barriers. The impacts of these barriers also seem to be influenced by who the obstacle is actually faced by, such as public organizations, firms or individuals (Weber, 1997). Moreover, it has to be considered in the analysis what kind of action is hindered, such as buying more efficient applications or imposing energy taxes (Weber, 1997). Although firms are choosing the cheapest way of abating emissions, market failures such as unpriced costs and benefits or misplaced incentives (Brown, 2001) contribute to the efficiency gap.

Marginal abatement cost curves make a contribution to overcome at least one main barrier to energy efficiency: awareness and information. One of the strengths of MACCs is their ability to provide information about energy saving opportunities as well as costs involved. The relationship between CO₂-e abatement and cost raises the awareness of the manifold mitigation possibilities in all economic sectors and addresses individual persons as well as decision-makers in public and private sector and policy-makers on all levels. MACCs are regarded as an appropriate way to communicate measures to improve energy efficiency (McKinsey, 2007; Stern, 2007).

2.2. The usage of MACCs

Abatement cost curves are a common way of disseminating the results of studies regarding climate protection measures and their costs (Barthel et al., 2006; Criqui et al., 1999; Den Elzen and Both, 2002; Kuik et al., 2009; McKinsey, 2007; Morris et al., 2008; Stern, 2007). The first abatement cost curves were developed in the late 1970s to reduce oil consumption after the two oil price shocks, and in the early 1990s they were applied to calculate electricity consumption savings (Farugui et al., 1990). There are basically two general ways to construct marginal abatement cost curves: one is a bottom-up approach using technical mitigation options and the other is to derive MACCs from computable general equilibrium (CGE) models.

The first approach looks for technologies and practices aiming at low GHG emissions including their costs and factors of limitation. Usually a list of GHG abatement measures is assessed in which the scope of sectors and analyzed mitigation options differ widely. CO₂-e abatement cost curves with regional or sectoral focus can be found for various countries. A comprehensive compilation of bottom-up MACCs was done by McKinsey & Company, an international consulting company, for countries all over the world and also on a global level, including over 300 options for CO₂-e abatement. For the UK, technological options were assessed for the household, service and transport sector (ENVIROS, 2005; Stern, 2007), highlighting a range of mitigation measures with negative abatement costs and concluding that the most significant absolute impact is from the retail sector. For the UK energy sector, Anderson (2006) emphasizes the good technological and institutional basis for the calculation of the curves. The conclusions confirm that a transition to a low carbon economy would not disturb economic growth and development. Barthel et al. (2006) give an overview of GHG abatement options for Germany in the household, service and industry sectors and conclude that there is a need for a more country-specific analysis of the market conditions. By constructing abatement cost curves of

Switzerland (Ziegler and Battig, 2009) the outcome indicates a huge abatement potential in the building sector through the construction of low energy houses.

CGE models are top-down economic simulation models. Basically, marginal abatement costs are defined as the shadow cost that is produced by a constraint on carbon emissions (Klepper and Peterson, 2006), whereas a more strict constraint would lead to higher marginal abatement costs. MACCs are derived by generating the costs associated with different levels of reductions (Klepper and Peterson, 2006). The results depend to a large extent on the model structures and assumptions such as substitution possibilities between carbon and low-carbon technologies and their elasticity and endogenous or exogenous technological change (Anderson, 2006). Various studies using CGE models exist, focusing on different regions and time horizons. The robustness of different levels of abatement across regions and different scopes of emission trading was investigated by Ellerman and Decaux (1998). They produced MACCs from the MIT Emissions Prediction and Policy Analysis (EPPA) model. Their main finding is that CO₂-e marginal abatement cost curves are an appropriate means of detecting and evaluating different emissions-reducing measures and that the cost curves are unique for each country. Recent US data was analyzed by abatement cost curves also derived from the EPPA model (Paltsev et al., 2005) and later (Morris et al., 2008) in terms of their robustness regarding time and previously adapted and foreign policies. Their main findings suggest that MACCs are affected by policies abroad and by policies in the past and depend on whether they include only CO₂ or all GHG emissions. Klepper and Peterson (2006) use abatement cost curves to establish a cross-country relationship through world energy prices. The results show that national MACCs depend on the abatement levels in the rest of the world through changes in worldwide fossil fuel prices and that MACCs are largely affected by the defined emission targets.

A good overview of US possibilities for mitigating GHG emissions is set out in the Annex to the White Paper “Cost effectiveness Under the Global Warming Solutions Act” (California Air Resources Board, 2008), in which a wide range of existing national and state CO₂-e abatement cost curves is summarized. The conclusion of one of the latest overview studies on abatement cost curves (Kuik et al., 2009) is their dependency on the stringency of the stabilization target, the emissions baseline, the time profile and the number of energy sources, while also emphasizing regional disparities.

3. Methods and data

A marginal abatement cost curve is defined as a graph which depicts the costs of abated CO₂-e on the y-axis and the last unit of emission abatement for varying amounts of emission reduction on the x-axis (Kesicki and Strachan, 2011). The measures considered are ranked according to their costs of abatement: marginal abatement cost curves depict the first ton which can be abated at lowest cost ranging up to the “most expensive ton”. A negative sign in the results means a financial advantage for the new technology which stems from lower energy costs whereby other benefits such as the residual value of the ‘old’ technology were not included. Dividing the additional positive or negative costs by the CO₂-e savings produces the CO₂-e unit costs of abatement. A positive value of a single measure therefore means that the life-long discounted costs of investment with the lower emissions are higher than the energy costs saved. The negative value describes a win-win situation in which the new technology causes fewer emissions, and the sum of energy costs and the discounted costs of investment are less than the energy costs of the old technology. In this case, the

introduction of the new technology leads to lower emissions and to a financial advantage. Marginal cost-of-abatement curves can also be seen as a method for describing a cost–benefit relationship where the cost of abatement corresponds to the “costs” and the amount of avoided CO₂-e to the “benefit”.

For constructing the MACC a technically oriented bottom-up approach was used by assessing technological options of mitigation of today and their related costs. This bottom-up approach makes it possible to feature a large number of discrete energy technologies for being able to substitute energy carriers, for process substitution or efficiency improvements (Böhringer and Rutherford, 2008). The aim of this study was to find out the theoretical, technical feasible mitigation potential of today by technological mitigation options of today without considering any economical or institutional restrictions.

Basically, the considered measures were chosen regarding their CO₂-e saving potential, energy saving potential or widespread common use. Static modeling assumptions were used to conduct the calculations for deriving costs and saving potential of mitigation measures. In so far the results were derived by comparing the ‘old’ technology (meaning the presently used technology with high CO₂-e emissions) with a respective ‘new’ highly efficient technology with less CO₂-e production which replaces the ‘old’ one.

For the options in each sector it was necessary to make specific assumptions in order to be able to calculate the costs of abatement these options have.

3.1. Household and service sector

3.1.1. Selection of abatement options

In the household sector, we identified the areas with the most energy consumption, namely heating and electricity for household appliances. To reduce CO₂-e emissions from heating, households face two options: insulations of buildings and/or switching to an environmentally less harmful heating system. To include both options, we developed a scenario which is explained in detail in Step 8. The choice of household appliances was guided by how widespreadly they are used, therefore we included refrigerators, dishwashers, washing machines, dryers, televisions and also energy light bulbs. In the service sector, the abatement options also focus on heating and electricity and we therefore included the efficient use of management systems for electricity and the replacement of heating systems.

3.1.2. Specific assumptions

When calculating the measures in the area of building insulation a differentiation was made between single and multiple occupancies and their specific abatement potentials.

3.1.3. Comparison of old and new technologies

Firstly, a comparison between a non-insulated house and an insulated house was conducted. Subsequently, where data was available, all fuel switch options of heating systems were calculated. We specifically focused on changing the heating systems using oil, gas, all sorts of coal and electricity to either a more efficient heating system using the same fuel or to pellets as a common representative for a zero emission technology (see also Table 1). No data was available for the specific energy demand and its corresponding CO₂-e emissions in the case of brown, cold and wet appliances currently used in Austrian households. Instead, the energy demand of the most inefficient device available on the market was compared to the highest efficiency one available. In the service sector, the comparison of the two measures was

Table 1

Assumptions about fuel switch in the heating systems of households.

<i>Single occupancies</i>			<i>Multiple occupancies</i>		
Fuel switch from	To	In % of all users	Fuel switch from	To	In % of all users
Oil	Gas	35	Oil	High-efficiency oil furnace	20
	High-efficiency oil furnace	20		District heating	50
	Pellets	35		Pellets	30
	Heat pump	10		High-efficiency gas furnace	80
Gas	High-efficiency gas furnace	100	Gas	District heating	20
Coal (all coal types)	Pellets	100	Coal (all coal types)	Pellets	100
Electricity	Pellets	100	Electricity	Pellets	100

conducted between buildings without efficient electricity use or efficient heating system and buildings which make use of them.

3.2. Transport

3.2.1. Selection of abatement options

All regarded measures are technical ones focusing on increased efficiency. Sixty-one single measures were identified for cars and trucks including e.g. engine improvements, lightweight interior components and rolling resistance reduction. Measures from the areas of demand, fuel carbon intensity or modal split were not calculated.

3.2.2. Specific assumptions

Measures regarding efficiency improvements of cars could be clustered into efficiency improvements, the switch to the most efficient car or truck in the regarding vehicle category, and a switch to hybrid cars.

3.2.3. Comparison of old and new technologies

As reference for comparison, average values for cars and trucks were used e.g. regarding their average annual consumption of driven kilometers and their respective CO₂-e emissions.

3.3. Energy

3.3.1. Selection of abatement options

The four measures are intended to substitute the corresponding CO₂-e emissions of the usual electricity mix by a carbon free electricity production by hydro power, wind, photovoltaic and solid biomass. Only one measure was considered as an example for heat production, namely the use of solar heat. The building of new large hydro power plants was not regarded as an ecologically sustainable alternative, therefore only small hydro power plants were considered when assessing the potential from hydro power. As geothermal heat in Austria has only a very small potential it was not considered in this study.

3.3.2. Specific assumptions

As in other sectors there was no consideration of the environmental impact of the construction of new power plants or photovoltaic panels. Therefore, a mitigation level of 100% was assumed. Further, all existing power plants of renewable energy were assumed to persist.

3.3.3. Comparison of old and new technologies

It was assumed that the electricity produced by various renewable energy sources (hydro power, wind, photovoltaic and solid biomass) could replace the same amount of the normally used electricity mix in Austria. For the measure solar heat, the Austrian heating mix consisting of oil, gas, coal, district heating and

electricity is replaced by solar heat. When estimating the costs of new power plants on a national basis we used the investment costs per MW of the respective power plants. The maximal technical potential was derived from various potential studies, and the already installed capacities were subtracted.

3.4. Steps necessary for deriving the MACC

3.4.1. Step 1: Description of status quo

Every single energy consumption activity is described by energy use per year, by its energy cost per year (based on 2007 energy prices) and its CO₂ equivalents. This data of a single measure is then multiplied with the amount available in Austria in order to get the overall impact on a national level. For example, the energy use of a refrigerator on average was multiplied by the according number of refrigerator used in Austria resulting in national energy demand of refrigerators.

3.4.2. Step 2: Description of 'new' technology

As above, energy use per year, energy cost and CO₂ equivalents are indicated and then calculated with the according multiplier on a national level.

3.4.3. Step 3: Impact of the replacement of the 'old' by 'new' technology

In order to be able to see the impact of the new technology, the following parameters are calculated by subtracting the 'old' from the 'new' technology, resulting in saved energy per year, saved energy costs per year, and saved CO₂ equivalents.

3.4.4. Step 4: Calculation of total costs

For deriving the yearly cost of a measure, a full cost pricing was conducted which includes the costs of investment, specific lifetime of a measure and a discount rate of 4%. Subsequently, the yearly energy costs are added.

3.4.5. Step 5: Total cost savings

For deriving the total cost savings, the calculated total costs of the 'new' technology per year are subtracted from the energy costs of the old technology. A positive value means that discounted investment costs plus energy costs of the new technology are cheaper than the energy cost of the 'old' technology; a negative value means that total cost of 'new' technology are more expensive than the energy cost of the 'old' technology.

3.4.6. Step 6: Deriving the €/CO₂-e ratio

This ratio gives the cost of CO₂-e abatement: total cost savings per year divided by the abated CO₂ equivalents per year.

3.4.7. Step 7: Aggregation of measures

In order to provide a clearly represented picture of the calculated measures, they were aggregated where many sectoral measures were present. In the household sector, single measures in the field of cold and wet appliances and in the field of brown appliances could be aggregated to one measure respectively, and also in the transport sector in case of trucks all single measures could be summed up to one aggregated measure without any overlapping. The aggregation of several measures to one single measure holds the danger of overlapping and double counting of CO₂-e emission reductions. To avoid this danger it is necessary to identify all interdependent and competing measures and subsequently to subtract the double counted CO₂-e emissions. The regarded single measures in the area of cars consist of technical measures improving efficiency, a switch to cars with hybrid drive and a switch to the most efficient car in the regarding vehicle category. It was easily possible to cumulate the single measures within these three categories, but it would lead to overestimated CO₂-e abatement potential if these three categories were added up. Most efficiency measures are only valid with a certain motor and are not applicable to hybrid cars, which already use the most efficient technology. Therefore, the following assumption was used for aggregation: 50% of the cars switch to the most efficient car in the regarding vehicle category, 35% undergo efficiency improvements, and 15% are replaced by hybrid cars. The result leads to one aggregated measure for cars. This procedure provides the advantage that all measures of one sector and also sectors themselves can be added up without providing an exaggerated saving potential.

3.4.8. Step 8: Development of scenarios for the household sector

A special feature was the calculation of emission saving potentials through a two step method for developing and assessing consistent scenarios in the household sector. Single measures in the household sector in the area of building insulation for single and multiple occupancies were calculated on the one hand, and single measures regarding fuel switch in heating systems on the other. Based on the knowledge how many households use which heating system (Statistics Austria, 2007a), various fuel switch measures could be calculated on a national level. As a next step, we combined the insulation measures with fuel switch measures in the respective heating systems: the insulated less energy demanding buildings undergo a change in their heating systems to low or zero emission energy carriers or switch to more efficient heating systems. In order to calculate the respective costs and emission savings without any overlappings, assumptions have to be made how many single and multiple dwellings would change to which heating system. Table 1 gives an overview of these assumptions.

The calculations of the single measure 'building insulation of single occupancies' result in a relative mitigation potential of 48%. Therefore, the lower heating demand (in kW h/m²a) requires less energy which also lowers the primarily calculated saving potential of the single fuel switch measures by 48%. Next, all single fuel switch measures with the lower potential were calculated, resulting in fuel switch measures with lower energy savings and mitigation potential than in non-insulated buildings. Finally, all single fuel switch measures together with the single measure 'building insulation of single occupancies' could be added without giving an overestimated mitigation potential. The same procedure was used for multiple occupancies.

3.5. Main assumptions for deriving the MACC

3.5.1. Timing

The focus of the study was to assess the overall CO₂-e abatement potential which one specific measure could have on a

national level if it was to be implemented completely instead of the 'old' technology. This means a market penetration rate of 100%. It was assumed that the measures are completely implemented today.

3.5.2. Technology

As outlined above, only technologies or efficiency improvements available today were considered for statically calculating the feasible mitigation potential of today.

3.5.3. Operating expenses

For the investigated measures in the sectors households, service and transport, the operating expenses were assumed to be the same for the 'old' and the 'new' technologies and consequently, they were not included in the calculations, e.g. single dwellings face the same operating expenses (liquid waste fee, disposal service etc.) whether insulated or not. In the energy sector, operating expenses and also the cost for fuel in case of solid biomass were included when calculating the total yearly cost.

3.5.4. Energy

The calculations of the specific measures are based on the demand of end use energy and its related costs. Except in the energy sector, the production of primary energy was the starting point for deriving the abatement potential.

3.6. Limitations of this study

3.6.1. Cost level

For renewable energy sources, the investment costs differ widely depending on where the power plants are located. We did not pay attention to this fact and used average investment costs instead. Also the actual capacity utilization has a wide range depending on the location of power plants which was not considered in the calculations of the respective measures in the energy sector.

3.6.2. Prices

Energy prices and investment costs are used from the year 2007, therefore the curve might look different with prices of today.

3.6.3. Disposal costs

Any sort of disposal costs of the 'old' technology were not considered in the calculations.

3.6.4. Incremental introduction

When introducing the 'new' technology no incremental introduction was assumed such as learning curves or gradual market penetration and moreover, no natural exchange rates of 'old' technologies were considered. Further, we did not pay attention to behavioral aspects, institutional barriers or market imperfections.

3.6.5. Business As Usual scenario

There is no specific description of a Business As Usual scenario which would outline these measures that would be taken anyway.

3.6.6. Emissions

The actual emissions in the production process of certain technologies were not included in the calculations, e.g. production of solar cells.

Many specific sources for primary data were needed for deriving the MACC. The most important variables needed for all sectors were derived from different sources: energy demand for the inefficient 'old' and the efficient 'new' technology (Lechner

et al., 2004; Lang, 2007; Statistics Austria, 2007a, 2007b; Topprodukte, 2007), cost of different energy carriers in 2007 prices (Statistics Austria, 2007a; IWO, 2007), emission factors (Federal Environment Agency, 2003; GEMIS, 2000), and cost of investment in 2007 prices [in household and service sector cost of insulation (Lechner et al., 2004; Lang, 2007; Schriebl, 2007); various settings of change of heating systems (Lechner et al., 2004), household appliances (Topprodukte, 2007); transport sector (EC Transport, 2001; OECD, 2005), energy sector (Faninger, 2006; Nakicenovic et al., 2007; Fechner and Lugmayr, 2007)]. The multipliers necessary for calculating the overall abatement potential from single case to national level were derived from Statistics Austria (2006, 2007b), Lang (2007), and Schriebl (2007).

4. The usefulness of MACCs

The method of presenting CO₂-e abatement potentials in form of bottom-up MACCs is challenging as it requires receiving the necessary data for conducting the calculations. If this requirement is fulfilled, MACCs give a clear picture of cost and amount of CO₂-e mitigation options. Each country has its own specific abatement cost curve independently of other countries' mitigation potential (Ellerman and Decaux, 1998). Although emission reducing targets are a global necessity, it is essential to consider a region specific abatement potential and its costs. How far this goal can be reached with abatement cost curves is discussed by critically reflecting on the usefulness of such curves. The following pros and cons should be kept in mind when looking at the presented results.

4.1. Advantages of MACCs

4.1.1. Awareness

CO₂-e abatement cost curves are a suitable method for increasing the transparency and awareness of the availability and effects of environmental technologies, especially in a win-win scenario for the consumer and the environment (Beaumont and Tinch, 2004). When introducing a new technology, CO₂-e abatement cost curves provide a basis for the understanding of available technologies and their related costs and resulting benefits. This environmental knowledge should encourage people to make use of the less polluting alternatives. Rational economic agents would aim to achieve abatement at the least cost possible, which may also involve a mixture of different measures, as they affect several fields of daily life. Besides, both consumers and politicians should have the freedom to choose between various options and decide on the one that is most suitable to their own interests.

4.1.2. Costs

It is sometimes argued that greenhouse gas mitigation options are "costly" without sufficient specification. Abatement cost curves depict more precisely the volume of costs since they also state the negative costs of abatement. Due to high investment costs, some mitigation options may be seen as very expensive although over time it is possible that they will be more cost-effective than initially cheap measures (Beaumont and Tinch, 2004). The abatement curves highlight this effect, which may otherwise be overlooked.

4.1.3. Recommendations

The underlying calculations provide a clear picture of the abatement options and it is possible to carry out a straightforward calculation if all data is available (Ellerman and Decaux, 1998). The results can be seen as investment guidelines for consumers, entrepreneurs and politicians. Depending on the level of aggregation the amount of greenhouse gases abated by each measure is

depicted. It also clearly shows which is the next, more expensive technology which must be applied in order to reach an additional abatement.

Given the advantages MACCs provide they are increasingly used to depict abatement options for several sectors and countries. Although extensive technological details are used there is an easy understanding of technology-specific abatement curves. Their strength lies in the presentation of the abatement potential and its related costs in a comprehensible way to politicians and other decision-makers (Kesicki and Strachan, 2011).

4.2. Disadvantages and potential pitfalls of MACCs

Although abatement costs curves provide many advantages, account must also be taken of some important issues that they cannot cover. The inherent structural weaknesses of the static model neglect the following aspects:

4.2.1. Diffusion

Calculating a specific amount of money that should be invested to achieve a certain reduction potential does not take into consideration the difficulties in penetrating the 'technology market'. The diffusion rate plays an important role in the overall effectiveness of the implemented measure. The related time factor depends on a wide range of variables such as legal compliance, policy incentives and the market structure, to name but a few.

4.2.2. Compatibility

Abatement technologies are not always compatible either with the current technologies or with a certain mixture of technologies. This lock-in effect may lead to increased costs when implementing the abatement measure (del Río González, 2008). In this study we focused on technologies which can easily be implemented with the existing technologies. More generally speaking, certain technologies are more cost-intensive in particular regions.

4.2.3. Production

On the basis of a (theoretical) 100% penetration rate of the 'new' technology, it could be expected that the CO₂-e emissions level will fall by exactly the amount that engineers had calculated to derive the CO₂-e abatement costs. Unfortunately, this is not the case. Account is not usually taken of the fact that the production of certain energy efficient devices itself requires (sometimes a significant amount of) energy. The emissions induced by the production of the intermediate inputs ('technologies') also have to be considered when deciding on policy actions (Sonntag and Schubert, 2008).

4.2.4. Energy prices

If energy prices change radically the cost curve turns to the left and makes it even cheaper to invest in a climate-friendly technology. Therefore, higher fossil fuel prices favor low carbon options (Stern, 2007). The contrary happens with a decline in the energy prices: this development would lead to a shift to the right, making GHG abatement more expensive and the financial incentive to investments weaker (ENVROS, 2005). Energy market prices are also found to influence consumer decisions on energy consumption: a persistent increase in the energy price leads to a more energy efficient adoption (Gillingham et al., 2009) by replacing high energy consuming devices with more efficient ones. A special case is electricity supply (Anderson, 2006) because the abatement potential depends on the source used for electricity production and its related emissions. If the CO₂-e emissions from the electricity production process diminish the potential for any further

mitigation, costs rise because a smaller amount can be abated at the same costs.

4.2.5. Ranking by costs

One of the core elements of CO₂-e abatement cost curves is a ranking of the measures that only relies on the costs of the abated CO₂-e and fails to consider the absolute amount that can be abated. The policy recommendation that can be drawn is simply to implement the cheapest measure first, preferring measures with a lower total saving potential but more cost-effective than those with a higher GHG saving potential in absolute terms. One empirical example is the use of low energy light bulbs, which has been analyzed in many studies (Joosen and Blok, 2001; Barthel et al., 2006; McKinsey, 2007; Stern, 2007) as well as in ours, and which proves to be one of the cost efficient measures with very low costs of abatement. The potential saving amount is low compared to other measures, but nevertheless national and European energy policies are introducing regulations that will limit the use of conventional light bulbs step by step over the years to come. Also for competitive reasons it is recommendable to prefer cheaper contributions to CO₂-e mitigation but it should be kept in mind that it is not only the costs that are the decisive factor. Political advice should also include measures with a high technological potential, such as photovoltaic systems, in order to achieve mitigation targets and to reduce the costs by increasing market diffusion.

5. Results

The calculated measures differ widely in financial costs and in amount of greenhouse gas emissions avoided. Summing up, the results set out in Fig. 1 show that the eight measures below the 0° line show negative costs of abatement and can lower emissions by 18.5 Mt CO₂-e. The interpretation of the first measure can be construed in the following way: the first 0.2 Mt CO₂-e can be abated at a profit of 694€/t CO₂-e by the introduction of efficient

electricity systems in the service sector, the next 0.6 Mt CO₂-e at a profit of 658€/t CO₂-e by using low energy light bulbs and so on.

5.1. Household sector

Saving potential was found in the fields of building insulation, fuel switches in heating, efficient brown, cold and wet appliances and lighting, which can be seen in detail in Fig. 1. The accumulated savings potential without overlapping emissions is 11.44 Mt CO₂-e from which 4.46 Mt CO₂-e can be avoided with profit of abatement and 6.98 Mt CO₂-e with cost of abatement.

The biggest GHG mitigation potential could be achieved by insulating single dwellings followed by fuel switches of the heating system (see measure 10 in Fig. 1), which could reduce greenhouse gas emissions by 6.6 Mt CO₂-e. The cost of abatement is calculated at 154€/t CO₂-e (see also Table A1 in Appendix A). Furthermore, an enormous reduction would be provided by insulating and switching fuel of multiple dwellings with emissions avoided of 4 Mt CO₂-e and profits of abatement of 72€/t CO₂-e. The overall mitigation potential in the building sector sums up to 10.6 Mt CO₂-e which is comparable to the Swiss mitigation potential of 11.3 Mt CO₂-e (Ziegler and Battig, 2009). If single measures are compared with other studies the results are similar: building insulation of multiple dwellings has a cost of abatement of –81€/t CO₂-e by decreasing the yearly heating demand from 122 to 48 kW h/m², whereas McKinsey (2007) has a lower cost of abatement with –133€/t CO₂-e but only reduces heating demand to 70 kW h/m² (McKinsey, 2007). In case of building insulation for single dwellings the calculations result in 229€/t CO₂-e, whereas in Barthel et al. (2006) cost of abatement is given at a comparable number of 200€/t CO₂-e. It is important to consider that the abatement potential in case of single and multiple dwellings is likely to be overestimated. The reason lies in the long term nature of building insulation and of fuel switches in heating systems because the assumption of a 100% market penetration ignores recently conducted building insulation or fuel switches in heating systems. Nonetheless, the theory of sunk costs suggests that these costs should not be regarded in future investment decisions,

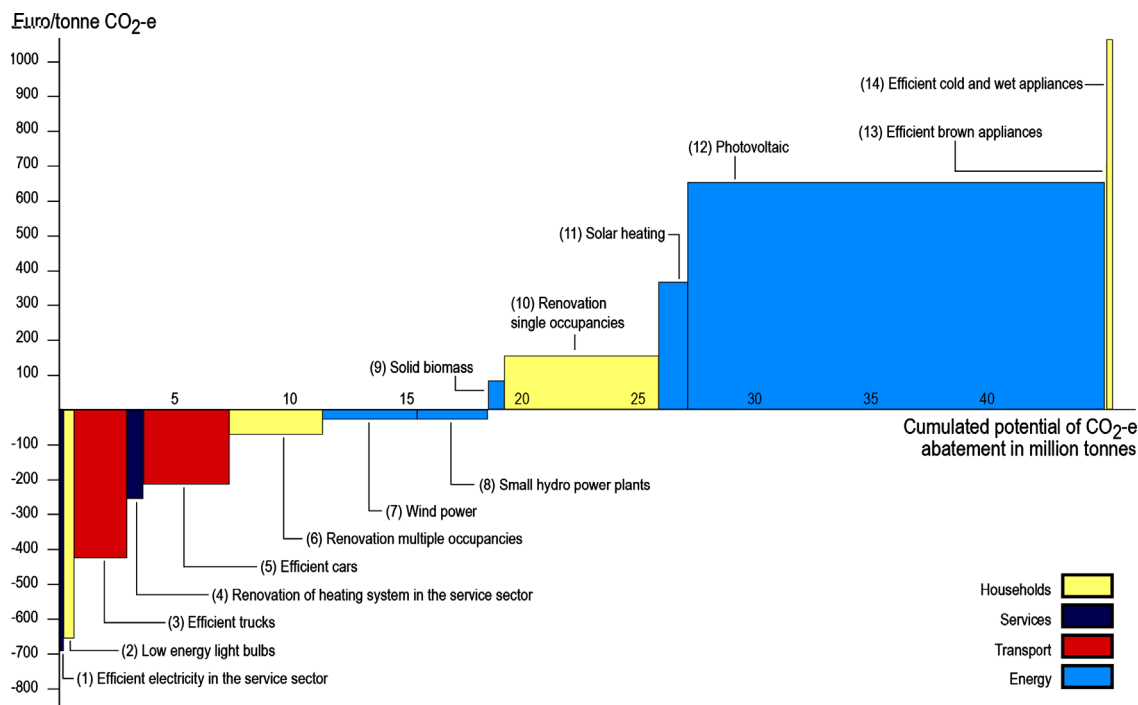


Fig. 1. CO₂-e abatement cost curve for Austria as of 2007.

therefore it would lead to a suboptimal result not to invest in these abatement options. However, the results would have differed if replacement rates had been considered in the construction of the MACC. Although the financial cost for single dwellings is positive (notice that they are negative for multiple occupancies), policy makers would be well-advised to invest in this alternative e.g. through financial incentives to make it more attractive for house-owners. In the case of Austria, there are governmental subsidies for building insulation but experts doubt their overall effectiveness due to the small amount of money provided. If we look at the results of the single fuel switch measures, the recommendation can be made to change the heating system from electricity to biofuels (the example calculation was made with wood pellets) because it was the cheapest fuel switch measure with a cost of abatement of $-194\text{€}/\text{t CO}_2\text{-e}$. With a share of 7.8% of all heating systems in Austria (Statistics Austria, 2001) it would be possible to avoid 0.6 Mt $\text{CO}_2\text{-e}$ a year. If the price for fossil fuels increases, the cost of abatement falls and makes it more attractive to invest in a more environmentally-friendly heating system. It should be stressed again that this does not mean that the cost of investment is lower but that the relation between the saved emissions and the cost of abatement is more favorable.

The most cost efficient alternative is the use of low energy light bulbs which could save up to 88% of energy and of the related emissions. This option also shows one of the most efficient profits of abatement, i.e. $658\text{€}/\text{t CO}_2\text{-e}$, although the absolute $\text{CO}_2\text{-e}$ emissions avoided are only calculated at 0.6 Mt $\text{CO}_2\text{-e}$. In McKinsey (2007), the cost of abatement is calculated as $-156\text{€}/\text{t CO}_2\text{-e}$ but in their report it was admitted that this measure would have been less expensive when calculating with full life-time instead of only 4 years (McKinsey, 2007). Nonetheless, based on these findings, the gradual prohibition of the production and selling of conventional light bulbs and pearl light bulbs beginning in September 2009 as introduced by the European Union is—for obvious environmental reasons—a step into the right direction (European Commission, 2009).

The saving potential in the field of brown, cold and wet appliances is comparably low and amounts to 0.37 Mt $\text{CO}_2\text{-e}$ (see measures 13 and 14 in Fig. 1) at the very high cost of $702\text{€}/\text{t CO}_2\text{-e}$ for brown appliances and $1063\text{€}/\text{t CO}_2\text{-e}$ for cold and wet appliances (see also Table A1 in Appendix A). As mentioned in Section 3 the high abatement cost is the result of a lack of data for comparing the 'old' with the 'new' technology. It can be assumed, therefore, that the saving potential is higher because the old appliances are more energy-intensive than even the most inefficient ones on the market nowadays, which were used for the calculation of $\text{CO}_2\text{-e}$ abatement costs. The energy consumption of the new appliances should be a decisive criterion for all consumers to consider.

5.2. Service sector

The most efficient measures in the service sector are the efficient use of management systems for electricity and the replacement of the heating systems. The most beneficial turns out to be the introduction of efficient electricity systems with a profit of abatement of $694\text{€}/\text{t CO}_2\text{-e}$ and emissions avoided of 0.2 Mt $\text{CO}_2\text{-e}$ (see measure 1 in Fig. 1). Through replacement of the heating system, 25% of the energy used can be saved, which results in a $258\text{€}/\text{t CO}_2\text{-e}$ profit of abatement. Like in other studies (Lechner et al., 2004) it can be shown that measures concerning buildings in the service sector are amongst the most cost efficient ones. There is also an energy saving potential in the insulation of buildings but as there is insufficient data available it was not possible to quantify the saving potential. The same holds true for the fields of electrical appliances in offices, lighting in buildings

and streets and cooling systems (Joosen and Blok, 2001), where no data is available for Austria, either. It can be assumed that the saving potential in the service sector is much higher than could be calculated and that all private and public authorities are expected to minimize the costs for their organization by implementing the cost and energy efficient solutions.

5.3. Transport sector

Only technical improvements concerning efficiency and fuel use were calculated for the $\text{CO}_2\text{-e}$ abatement costs. Policy measures like the extension of public transport or any alternatives concerning a fuel switch of cars and trucks could not be considered in the calculations. All single measures for cars and trucks were summed up to one single measure, without overlapping potentials, and both show negative costs of abatement (trucks -428 and cars $-216\text{€}/\text{t CO}_2\text{-e}$; see measures 3 and 5 in Fig. 1). Due to the aggregation of all single measures no comparison to other studies could be conducted. The emissions saved by full implementation are 6 Mt $\text{CO}_2\text{-e}$.

Especially in Austria, where emissions from the transport sector nearly doubled last 20 years, it is important to figure out that nearly one-third of sector's emissions could be avoided by technical measures only. The aggregate measure for trucks suggests avoiding 2.3 Mt $\text{CO}_2\text{-e}$ which is based on the assumptions about reduction on fuel demand due to weight reduction, rolling resistance reduction, engine improvements, and aerodynamic drag reductions. In case of the aggregate measure for cars, the result differs depending on the assumption how many cars undergo which efficiency measures. If all cars only undergo efficiency improvements total abatement potential would be even higher with 5.5 Mt $\text{CO}_2\text{-e}$ in comparison to the case where all cars switch to the most efficient car in the regarding vehicle category where the abatement potential is calculated with 2.9 Mt $\text{CO}_2\text{-e}$. Due to the increase in fuel prices in recent years it is expected that the $\text{€}/\text{t CO}_2\text{-e}$ ratio becomes even less as higher energy prices favor carbon options. Nonetheless, the measures show which enormous abatement potential lies in these technical measures alone and that even without any radical change of the transport system it is possible to save enormous amounts of $\text{CO}_2\text{-e}$.

5.4. Energy sector

The results of the energy sector show that by using renewable energy sources for the production of electricity and by using solar heat 25.8 Mt $\text{CO}_2\text{-e}$ could be avoided, which is more than one quarter of Austria's overall $\text{CO}_2\text{-e}$ emissions. Within the identified measures, photovoltaics have the biggest capacity to avoid emissions, 17.9 Mt $\text{CO}_2\text{-e}$ (see measure 12 in Fig. 1). Unfortunately, this is still one of the most expensive alternatives with costs of abatement of $652\text{€}/\text{t CO}_2\text{-e}$. As the calculation was based on the theoretical assumption to include all roofs and facades available in Austria it can be assumed that the actual abatement potential is lower if areas with low efficiency are excluded. However, it can be expected that this technology will become cheaper within the next few years and that as a result the financial incentive to invest will increase. Electricity from small hydro power plants is seen as part of Austria's energy future. On the one hand, the costs of abatement at $-29\text{€}/\text{t CO}_2\text{-e}$ lead to the recommendation to invest in this technology, and on the other hand small hydro power plants also provide an alternative for regional energy autarchy. Further fields identified include wind power, which is also calculated at negative costs of abatement of $-31\text{€}/\text{t CO}_2\text{-e}$, and 4 Mt $\text{CO}_2\text{-e}$ could be avoided this way. These comparably low abatement costs (see e.g. McKinsey, 2007: $15\text{€}/\text{t CO}_2\text{-e}$) are due to the assumption that full technical feasible wind power potential is

exhausted. By electricity production from solid biomass 0.72 Mt CO₂-e can be avoided at a cost of abatement of 83€/t CO₂-e which is especially important in Austria due to its large amount of forested land. To tap into the full potential in electricity production would imply less dependency on electricity imports and less overall use of nuclear power and fossil energy sources. The option solar heating results in cost of abatement of 367€/t CO₂-e and an abatement potential of 1.25 Mt CO₂-e but it can also be expected that costs will decrease in the near future which would lead to cheaper cost of abatement.

The explicit goal of energy policy in most Western countries is an increase in the share of renewables in energy production. The abatement potential and its related costs serve as guidance for policy-makers about possibilities enhancing a less environmentally harmful energy production. Despite calculating with average investment costs for power plants of different renewable energy sources the results show nonetheless the huge abatement potential that could be achieved by using renewable energy sources for energy production.

5.5. Sensitivity analysis

To prove the robustness of the results a sensitivity analysis was conducted by varying three of the key parameters of the MACC: cost of investment, potential of energy savings, and discount rate. Three scenarios were developed where parameters varied according to different assumptions. Regarding estimates concerning future developments it is not very likely that these three parameters develop worse than previous calculated, therefore only more favorable scenarios were defined. Scenario 1 describes an optimistic scenario where improvements in energy savings were assumed with further 50%, a very favorable discount rate of 0.5% (using the same as in Stern, 2007) and a reduction of investment costs of further 50%. The measures of the energy sector were changed according to estimates of their potential in 2050 and according to learning rates leading to lower costs of investment which were especially low in case of photovoltaic. The resulting MACC shows that only two measures still have positive values: using biomass for electricity production results in 49.25€/t CO₂-e in comparison to originally calculated 83.03€/t CO₂-e which is due to lower efficiency improvements and lower savings in the investment costs than all other measures. The costs of abatement for photovoltaic result in 10.78€/t CO₂-e in comparison to originally calculated 652.42€/t CO₂-e which is the result of very high learning curves of the costs of investment of 75%. The overall abatement potential increases from 45.4 to 66.7 Mt CO₂-e. Scenario 2 is even more optimistic by assuming improvements in energy savings of further 80%, costs of investment decrease by further 75% and a discount rate of 0.5%. Again, different assumptions for the measure of the energy sector were assumed reflecting the lower energy saving potential of biomass which results in the only measure with positive abatement costs of 37.27€/t CO₂-e. The total abatement potential is 70.6 Mt CO₂-e which would correspond to the Austrian contribution of the goal of an EU-wide GHG emission reduction of 80% in 2050 to avoid an increase of global temperature of more than 2 °C. Scenario 3 is less optimistic with improvements in the potential of further 10%, a decrease of the costs of investment of further 10% and a discount rate of 2%. Even with pessimistic assumptions about learning curves and potential improvements only five measures show positive costs of abatement resulting in a total abatement potential of 52.64 Mt CO₂-e. The analysis has shown that the calculated emissions savings are likely to be improved as the literature analysis suggests favorable developments of all three parameters. If the assumption of a 100% market penetration is not fulfilled it could mean that it will be compensated partly by the development of the three parameters.

6. Conclusions and outlook

In the public debate it is commonly argued that measures for climate protection are cost intensive and are not really feasible alternatives in times of an economic crisis. By calculating CO₂ cost of abatement curves we have shown which measures provide a high potential of avoiding greenhouse gas emissions and what these costs are for each abated ton of CO₂-e. Eight measures with negative costs of abatement were identified that add up to a CO₂-e emission saving potential of 18.5 Mt CO₂-e in Austria. If this potential is fully exhausted it would even exceed the abated CO₂-e amount needed of 15.6 Mt CO₂-e to fulfill the Kyoto Protocol. An additional implementation of all the six measures with positive abatement costs would save another 26.9 Mt CO₂-e and 2007 emissions of 87 Mt CO₂-e (in 2009: 80.1 Mt CO₂-e) could be more than halved to 41.6 Mt CO₂-e (in 2009: to 34.7 Mt CO₂-e) through the 14 cumulated measures.

The results show the huge abatement potential that lies in energy efficiency measures. While no single technology or solution can solve the problem entirely on its own, they have an impressive potential when used jointly. The results emphasize the importance of energy efficiency measures and want to make a contribution to raise the awareness of the unused CO₂-e abatement potential. Imperfect and asymmetric information is considered as one of the main barriers in implementing energy efficiency measures. MACCs pose a possibility to provide information that is easy to communicate, and the advantage of energy savings and their positive or negative costs are visible at a glance. The specific Austrian CO₂-e abatement curve gives evidence to possible financial advantages in the areas of household appliances, transport, renovation of multiple occupancies and energy. Using this valuable information raises the transparency of energy efficiency measures.

Providing information is one first important step, and it is then up to the policy makers to enforce the dissemination of the results to the public and also to provide financial support to overcome a second barrier of implantation: capital constraints and access to capital. With financial subsidies, e.g. for the investment costs, it would be a societal sign to environmentally friendly enhancement. The detected measures with negative abatement cost should be the first to be focused on by monetary incentives or grants. This could be supplemented by the expansion of codes and standards regarding energy efficiency measures. If households as well as private and also public organizations face the problem of insufficient capital to invest in suitable incentives and grants, internal or external funding based on investment rules incorporating environmental guidelines and standards must be enforced.

The results of MACCs are often compared to current and future carbon permit prices to indicate their economic efficiency. The created market system of buying and selling certificates that allow emitting CO₂ is in the focus of critique by the following reasons: From an ecological point of view, carbon market lacks in incorporating all other GHGs which currently makes approximately one-fourth of all GHG emissions. Moreover, this system is not effective in terms of reducing GHG emissions as absolute emissions have grown and still are growing steadily in the economic sectors incorporated in emission trading. From an economic point of view, looking at the price levels only shows that current low prices of carbon certificates make them an economically efficient option to emit CO₂. But one of the reasons for the low price level is that too many allowances were issued at the beginning and further development shows that demand was lower than actual supply leading to a price level of nearly zero Euros in 2007 and nowadays of about 3€. Besides, the costs of transaction, information, and controlling needed for trading carbon permits are not reflected in the price level and valuing ecological impacts of CO₂ emissions is not incorporated at all. From a political point of view, the low price

Table A1
Results for CO₂-e abatement measures in all sectors.

Measures Units	Total cost of investment (€)	Total energy savings (kW h)	CO ₂ -e saving potential (tons per year)	Relative CO ₂ -e saving potential (%)	Costs of abatement (€/tons CO ₂ -e)
(1) Efficient electricity in the service sector	597,595,308.54	1,206,125,000.00	195,392	15	– 694.13
(2) Low energy light bulbs	778,128,438.75	2,758,582,425.00	446,890	88.3	– 657.78
(3) Efficient trucks	924,147,576.00	8,479,810,61	2,271,097	21	– 427.51
(4) Renovation of the heating system in the service sector	731,006,807.31	2,980,277,777.78	690,056	25	– 257.96
(5) Efficient cars	10,258,186,663.80	13,912,581,76	3,732,488	31.4	– 215.69
(6) Thermal insulation and fuel switch of multiple occupancies	17,622,319,923.00	15,163,750,836.83	4,013,669	63.4	– 72.35
(7) Wind power	2,805,985,000.00	^a	4,057,690	100 ^b	– 30.96
(8) Small hydro power plants	2,736,000,000.00	^a	3,051,230	100 ^b	– 29.27
(9) Solid biomass	449,460,000.00	^a	722,995	100 ^b	83.03
(10) Thermal insulation and fuel switch of single occupancies	54,303,605,067.38	23,286,523,533.54	6,628,316	55.9	154.22
(11) Solar heating	13,718,108,372.11	^a	1,246,014	100 ^b	366.76
(12) Photovoltaic	182,990,500,000.00	^a	17,936,200	100 ^b	652.42
(13) Efficient brown appliances	878,478,380.55	410,326,817.52	66,473	57.6	702.50
(14) Efficient cold and wet appliances	6,261,878,007.30	1,734,405,783.52	280,974	56.8	1063.17

^a Due to a change in the energy resources only there is no energy saving.

^b The underlying assumption is that in the energy production sector, energy from fossil fuels is replaced by zero carbon energy resources.

level does not give any incentive to avoid CO₂ emissions and to search for low-carbon options. Moreover, not all parties involved have the same power in price negotiations. Market power of some firms gives them the ability to manipulate prices, to collude or use mark-ups (Spash, 2010). Current poor institutional design of the carbon permit market does not contribute to an effective climate policy but hopefully framework conditions change enhancing a low-carbon policy.

By critically reflecting on the advantages and disadvantages of MACCs it could clearly be shown what MACCs can be used for. Their strength lies in the provision of transparent information and they can easily be compared with other MACCs. Any changes in energy prices, costs of technologies or policy responses are not incorporated in the calculations, which is a limiting factor on the advantages of MACCs. Although the likelihood of the calculated costs of the measures is very high we admit a certain uncertainty regarding future costs. An important contribution is the two step aggregation of measures in the household sector where we could calculate the CO₂-e abatement potential for the whole energy scenario. The results can further be compared to other research outcomes, and they underline the uniqueness of MACCs for every country.

Future research is needed to update the curves. Marginal abatement cost curves can be seen as a snapshot of the status quo and should therefore continuously be updated. New technological opportunities and lower costs of existing technologies should also be the basis of new calculations for deriving the costs of CO₂-e abatement. With an extended availability of exact data it would be possible to achieve a more solid scientific basis for making statements about the economic and ecological impacts of CO₂-e mitigation options.

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Appendix A

See Table A1.

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